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Original Article

APPLYING STRAIN-SENSING TECHNOLOGY FOR MONITORING AND DIAGNOSING PEEL-BASED DETERIORATION OF TILED EXTERIOR WALLS

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ABSTRACT

Various levels of deterioration can occur in buildings, because of aging or improper management. In recent years, the deterioration of tiled exterior walls of the buildings in Taiwan has become increasingly severe. This phenomenon not only reduces the aesthetic value of the city, but also threatens the life and property of the residents. However, current diagnosing techniques, including visual examination, tap tone diagnostics, and infra red thermography, for tile deterioration of the exterior walls require inspecting personnel to perform the tests with instruments. Exterior wall tile deterioration cannot be diagnosed objectively and scientifically, in real time. Therefore, this study proposed an innovative application of strain gauges for a real-time self-diagnosing of exterior wall tiles. This technique can serve as a smart inspection technological option for building administrators.

The experiment performed in this study comprised two phases. Phase 1, determined the voiceprint eigenvalue of the tiles on the exterior walls with varying levels of deterioration, and Phase 2 applied the strain sensing technology using strain gauges for monitoring the peel-based deterioration of the exterior wall tiles. Results of the sound diagnostics experiment in Phase 1 were converted and compared with corresponding strain variations of the tiled walls with varying deterioration levels. The diagram of deterioration symptoms of square tiles was further analyzed using the pathogenesis theory of quasi pathology. Results of this study can be used to provide real-time, consecutive, and scientific long-term monitoring. The research results provide a reference for developing future smart cities and for the Internet of Things; furthermore, this study also plotted a diagram of the deterioration symptoms, which can serve as a scientific basis of determination concerning diagnoses of exterior wall tile deterioration.

KEYWORDS: Exterior Wall Inspection, Strain Gauge, Tile Deterioration, Public Safety & Smart Exterior Wall

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INTRODUCTION

Buildings go through life cycles similar to human beings. Improper management combined with the aging of buildings can produce numerous problems related to deterioration, such as tiles falling off walls, which become increasingly severe (Figure 1). Tiles are a decoration material commonly used in Taiwanese buildings. Tile deterioration caused by various weathering factors (e.g., humidity, wind, and rain) not only reduces the aesthetic value of the building, but also threatens the life and property of the building users. In recent years, injuries caused by falling tiles have been frequently reported. Therefore, the Taipei City Government stipulated that for high-risk buildings aged ≥15 years, regular safety inspections and diagnoses of the exterior walls should be performed. The commonly applied current inspection techniques, such as visual diagnosis, tap tone method, and infrared

thermography, require inspection personnel to perform the inspection with instruments. The health conditions of a building can be determined only after subsequent processing, evaluation, and interpretation of the data obtained through the inspection. For cities threatened by the risk of building deterioration, such a complicated procedure is too slow for mitigating urgent hazards; thus, the public environment is constantly exposed to high risks of falling tiles.

Figure 1: Deterioration of Tiled Exterior Walls

To solve the aforementioned problems, this study adopted the acoustic analysis technique (AAT) to determine the corresponding eigenvalues of the voiceprints of simulated exterior wall specimens with varying levels of deterioration. In addition, the concept of preventive medicine was introduced in Building Medicine, to embed a strain gauge in tiled exterior walls to perform real-time, automatic, and continuous monitoring of the deterioration of tiled exterior walls (Chang, 2006). An analysis of the strain measurements was conducted using the pathogenesis theory of quasi pathology; a diagram of the square tiles' deterioration symptoms could then be plotted. This technique is expected to serve as a reference for future innovative techniques in real-time tiled exterior wall diagnosis, providing diagnosis personnel with an objective and scientific basis of determination.

LITERATURE REVIEW

Application of Voiceprint-Based Inspection Technology in Constructed Structures

Voiceprint-based inspection technology has been widely used in various applications. Regarding constructed structures, Grosse et al. (2010) used acoustic emission to inspect failures in the internal structure of bridges. Benavent et al. (2010) also employed acoustic emission to monitor and assess the low-cycle fatigue damage in reinforced concrete exterior beam-column sub assemblages. Farhidzadeh et al. (2014) used acoustic emission to monitor the entire pipeline lining system and evaluate the level of damage after an earthquake. This system can detect items that require maintaining, thereby ensuring the safe operation of underground infrastructure. Carpinteri and Lacidogna (2006) used acoustic emission to assess the damage to the structure and exterior walls of two Middle Age buildings. Aggelis et al. (2012) determined the corrosion of iron bars in a pre-stressed ground anchor by analyzing elastic waves. Tong et al. (2006) developed fast and effective nondestructive testing by analyzing the voiceprint produced from impact. Luo et al. (2006) proposed a non-destructive secondary acoustic emission-based method to inspect railroads or the hidden basic structure of buildings. In summary, current applications of acoustic inspection in constructed structures mostly involve detecting damage inside or on the surface of structures or embedded equipment, such as the deterioration of buildings' exterior walls. Thus, voiceprint technology is suitable for use in the surface inspection of exterior walls.

Inspection Technology of Buildings' Exterior Walls

Exterior wall-inspection technologies have received increasing attention in recent years; most of these technologies are non-destructive. For example, Chiang et al. (2016) proposed diagnostic strategies to enhance public safety by visually examining the deterioration of buildings' exterior walls. First, the D. E. R. visual examination technique was employed to evaluate deterioration; the condition indicator (CI) of the tiles on the exterior wall was then calculated, and the tap tone test was applied to examine locations where the diagnosis results were relatively ambiguous. Khan et al. (2015) performed a comprehensive inspection of the structure of exterior walls by using infrared thermography, acoustic emission, and ultrasonic techniques; an estimation of the deterioration of the exterior walls was obtained by combining the three sets of examination data. Regarding the application of the voiceprint-based inspection technology, Tong et al. (2006) examined the integrity of the tiles on the basis of the time-domain characteristics of the acoustic waves. Jiang (2009) considered that among numerous non-destructive inspection methods, the tap tone method, which simply involves analyzing tapping sounds, is the most convenient and cost-efficient. Another study used robots to perform exterior wall tile damage inspection, the results of which can be displayed on handheld devices via wireless transmission (Luk et al., 2009). Multiple inspection technologies have received substantial attention because of increasingly severe problems related to tile deterioration. Currently used methods include visual examination, tap tone diagnosis, and infrared thermography. However, all the aforementioned methods require related personnel to operate the handheld instruments or to install the mechanical equipment. Therefore, they cannot obtain timely information, and that the accuracy is susceptible to numerous environmental constraints.

METHODOLOGY AND EXPERIMENT DESIGN

The experiment performed in this study consists of two phases, namely sound diagnostics and strain measurement. In the first phase, the eigenvalues of hollowing in the walls were acquired by combining voiceprint technology with a tap tone test. In the second phase, strain measurement was conducted, and the results were compared with the eigenvalues of hollowing obtained from tapping with a constant force. A directional microphone was employed to record the sounds produced during tapping. Experiment results were subsequently analyzed using both voiceprint and strain-measuring technologies to identify the changes in the strain measurements yielded at various levels of hollowing-based deterioration.

Principle of Strain Sensing

A strain gauge is also referred to as a strain sensor. In engineering, commonly used strain-sensing systems comprise the following basic structure and operate according to the following principle. A foil grid with fixed resistance is attached to the surface of the tested object. When strain is applied to the tested object, the resistance of the foil wires accordingly changes. Equation 1 shows the relationship between the strain and resistance, where R is the resistance value, p is the resistance coefficient, l is the wire length, and A is the cross-sectional area of the wire. This study adopted a single-axis spot-based strain gauge (Figure 2). The advantage of this device is that it exhibits minor changes in its own resistance, and the disadvantage is that it cannot measure strain distribution of relatively large areas, when the tested object is relatively large. This type of gauge is more suitable for detecting the static and dynamic plastic strain of materials at a single spot.

$$R = \rho \frac{l}{A} \quad (1)$$

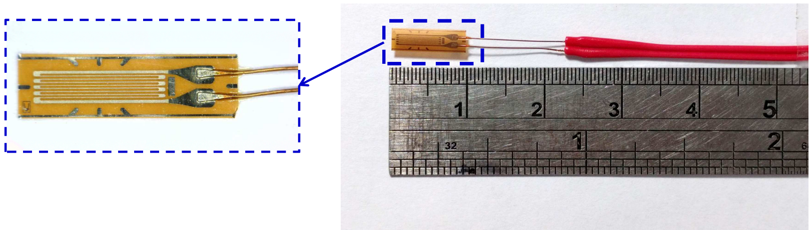

Figure 2: Single-Axis Strain Gauge

Experimental Design of Sound Diagnostics

This study combined voiceprint-based inspection technology and the tap tone method to measure the eigenvalue of the deterioration level of an exterior wall paved with 10 × 10 cm square tiles. First, the wall was tapped, and the sounds were collected using a directional microphone. Next, the voiceprint analysis technique was applied to obtain the eigenvalue. To ensure that a uniform tapping force is applied throughout the experiment, this study adopted a patented device developed by Chang (2014; Taiwan patent certificate number: TWM490003). The device is a tap auxiliary tool, in which, the base can be affixed on a vertical wall and the rod attached to the base can be let loose at various distances from the wall as a free-falling object to generate specific impact force. Figure 3 illustrates the tapping procedure. Regarding the specimen design, three 40 × 25 × 15 cm specimens were simulated, which exhibited three designated deterioration levels, namely 0%, 30%, and 70% of the hollowing rate. Different hollowing rates were simulated by stuffing plastic corrugated boards of various sizes at the back of the square tiles. Figure 4 shows the front and side views of an experiment specimen.

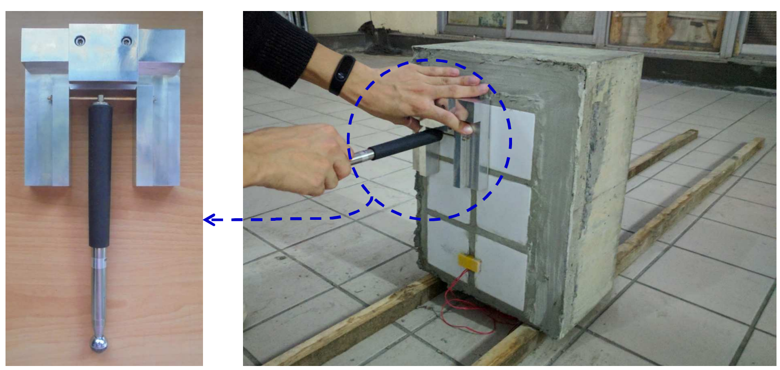

Figure 3: Demonstration of the Use of the Tap Auxiliary Tool

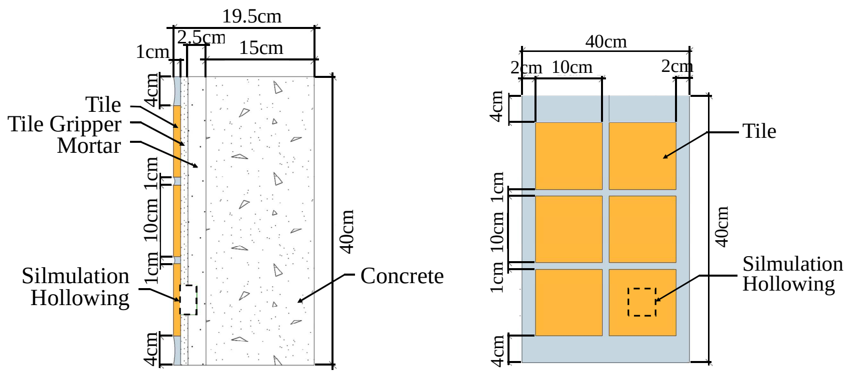

Figure 4: Design of a Specimen Simulating Exterior Wall Deterioration (Left: Sectional View; Right: Front View)

Experiment Design of Strain Measurement

This study adopted a strain gauge to measure the deterioration of the interface between the cement mortar and concrete. To avoid measurement errors caused by strain gauge embedding, strain gauges were not embedded until a metal testing medium was inserted to protect the gauge. A piece of aluminum sheet was adopted as the testing medium, and three-dimensional printing technology was used to apply the packaging design. The protected strain gauge and its passage were designed to lie between the concrete and gripper mortar of the exterior wall-simulating experiment specimen. Figure 5 illustrates the design of a tile strain gauge (TSG). The experiment signal-receiving human–computer interface was designed using Lab view. The interface enables the direct display of strain changes on the system screen. The experiment venue was the Civil Engineering and Water Conservation Hall of the Feng Chia University in Taichung, Taiwan (24.181157°N; 120.646730°E). Devices used in this experiment comprised a tap auxiliary tool, a directional microphone, a digital signal processor, and a laptop computer (Figure 6).

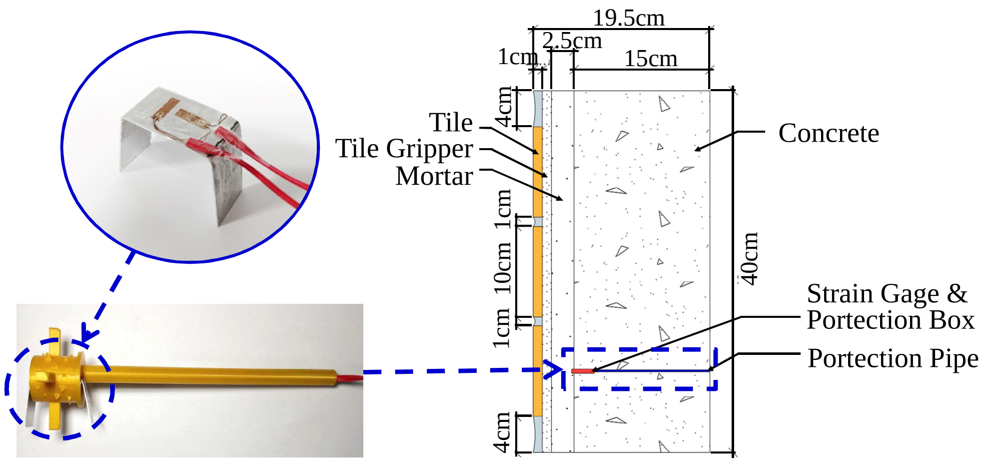

Figure 5: Design of the Strain Measurement Specimen

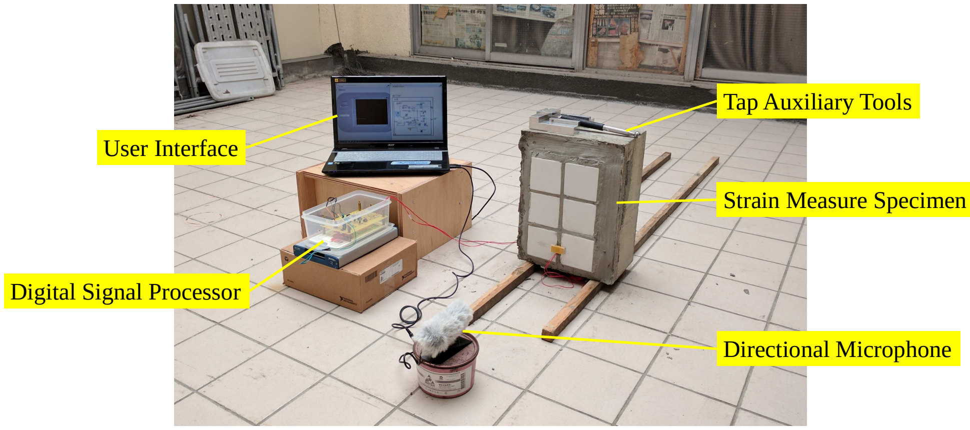

Figure 6: Experiment Venue and Equipment

RESULTS AND DISCUSSIONS

Analysis Results of Sound Diagnostics

The sound diagnostics experiment performed in this study involved the tapping of three specimens with varying designated hollowing rates (i.e., 0%, 30%, and 70%). For tapping duration, 15 voiceprint entries were collected, and each entry consisted of 5 taps; therefore, a total of 75 entries were recorded. Wave Surfer was adopted to analyze the experiment data. For specimens with hollowing rates of 0%, 30%, and 70%, the corresponding frequency range was 357–449, 3980–4341 and 4718–4987 Hz. Figure 7 shows the analysis results, which can be used as a reference for determining the corresponding eigenvalues of hollowing through the strain measurements in the second stage.

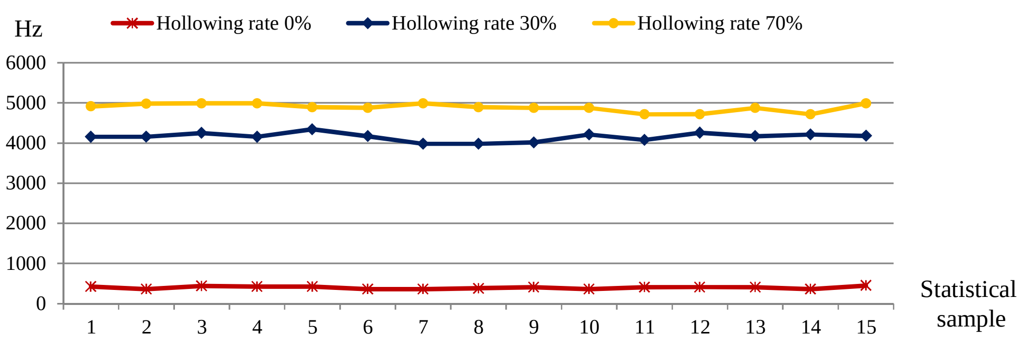

Figure 7: Line Chart of the Sound Diagnostics Experiment Results

Experiment Results of Strain Measurement

In the second phase, the strain experiment involved using a tap auxiliary tool to tap square tiles featuring simulated deterioration, and this tool was also employed in the sound diagnostics experiment. Considering the time needed for the strain gauge to return to stability after being compressed by tapping, the experimental procedure was designed as follows. Step 1: launch the program to collect initial data; this step determined the strain before tapping, which could then be compared with that after tapping. Step 2: tap on the specimens with simulated deterioration; the tap auxiliary tool was used to tap the specimen with identical force consecutively for 300 times at a frequency of 1 tap/second. Step 3: measure the strain; the strain was measured 3 min after 300 taps, so that the strain gauge could return to stability. When the square tile peeled off completely (e.g., after 1587 taps in this experiment), the strain-observing experiment was ended.

Figure 8 presents the converted results of the experiment performed in the second stage. The upper and lower horizontal axes represent the number of taps (N) and deterioration rate (D), respectively; the vertical axis represents strain (ε), which is a dimensionless quantity. This study applied the pathogenesis theory for comparing the characteristics of Stage Ⅰ and Stage Ⅱ. The corresponding relationships of these characteristics were divided into four stages. The initial strain was −0.004. In the process of deterioration, the strain oscillated between −0.005 and 0.003, which was then adopted as the background strain range of deterioration. The terminal strain measured when the tile peeled off completely was −0.002.

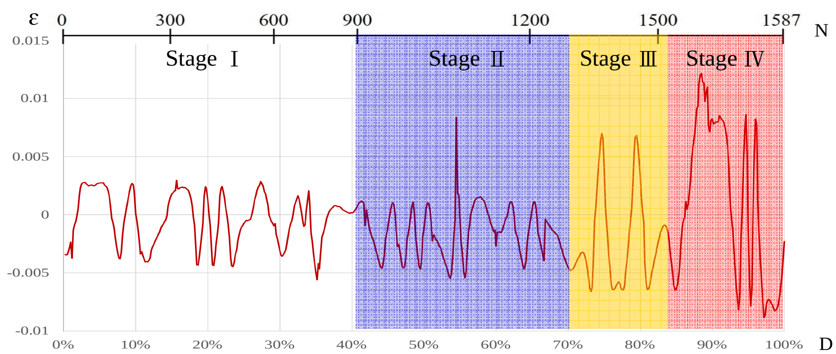

Figure 8: Line Chart of the Strain Measurement Experiment

DISCUSSIONS

After obtaining the corresponding eigenvalues of the varying hollowing rates through the voiceprint experiment in the first phase and determining the strain of the exterior wall tiles with varying levels of deterioration in the second phase, this study proceeded to discuss four perspectives, namely the pathogenesis of the square tiles, rate of symptom progression and attributes of symptoms, research limitations, and application cost estimation.

Pathogenesis of the Square Tiles

The pathogenesis theory investigates the pathogenesis of a disease, to determine its patterns and generally divide its changes into acute or chronic types. Through cross-referencing of the deterioration rates, number of taps, and strain variations, the deterioration process was categorized into four stages (Figure 8).

Stage Ⅰ

Tapping caused mild deterioration of the specimen in this stage; each tap approximately aggravated the deterioration by 0.03%. Strain variations remained in the background strain range. Before the strain experiment progressed to Stage Ⅱ, the effect of tapping on deterioration gradually declined. This was possibly because some space remained between the gripper mortar and concrete of the specimens. Although some recovery time was reserved following tapping, the specimen might have not fully recovered from the compressions.

Stage Ⅱ

Tapping caused greater changes in this deterioration stage; each tap approximately enhanced the deterioration rate by 0.075%. The first extensive change in strain was observed in this stage; however, the strain could still return to the background strain range after extreme oscillation. This was because, after the chronic influence of an external force (e.g.,

earthquake), the adhesive effect between the concrete and gripper mortar was reduced, and preliminary and temporary peeling could be observed.

Stage Ⅲ

In this stage, tapping caused an effect similar to that of Stage Ⅱ. Each tap approximately enhanced the deterioration rate by 0.075%. However, more than two considerable changes in strain could be observed in this stage. This was because, temporary peeling occurred more frequently, along with the continual decrease in the adhesive effect between the concrete and gripper mortar. The amplitudes of the strain waves were similar to those of Stage Ⅱ.

Stage Ⅳ

Tapping caused a significantly higher deterioration effect in this stage; each tap approximately aggravated the deterioration rate by 0.18%. In addition to more than two considerable changes in the strain, Stage Ⅳ exhibited substantially higher amplitudes than those of Stages II and III, namely an increase of approximately 30%. This stage came close to the damage point of complete peeling off; thus, the characteristics of Stage Ⅳ were considered as symptoms of the end-stage pathogenesis of exterior wall tile peeling.

Rate of Symptom Progression and Symptom Attributes

This study defined the high strain peaks in the deterioration process as the eigenvalues of deterioration-induced strain. The peak values ranged between 0.05 and 0.015. In addition, the use of the pathogenesis theory to examine this instance of pathogenesis revealed that the effect of the number of taps on deterioration rose significantly only after Stage Ⅳ. Complete deterioration was achieved in the end stage with merely 5% of the total number of taps. Therefore, this study inferred that the deterioration-induced peeling of exterior wall tiles progressed relatively mildly from Stage Ⅰ to Stage Ⅲ, and the phenomenon was aggravated markedly in Stage Ⅳ. From the perspective of Building Medicine, the rate of symptom development in the deterioration of exterior wall tiles is similar to that of acute diseases in human medicine. The symptoms are relatively inconspicuous in the early stages, and notable symptoms are exhibited only toward the end stage of the disease. In summary, the early warning time is fairly short. Without automatic monitoring, public safety hazards can hardly be identified and controlled in real time before they cause damage.

Research Limitations

This study, primarily confirmed the feasibility of using strain gauges to measure the deterioration of tiled exterior walls. A diagram of deterioration symptoms was also plotted. However, more simulation experiments should be conducted to develop a more accurate diagnosing model. In addition, among the numerous factors of deterioration, this study only simulated and investigated the effects of earthquakes as an external force. In the future, investigating additional factors of natural deterioration, such as acid rain, sunshine, weathering, temperature, and humidity, can facilitate the development of a diagnosing model that is more consistent with real-life situations.

Application of Cost Estimation

Regarding actual application, a set of single-axis spot-based strain-measuring devices comprises a TSG and signal processor, which cost USD$10 and USD$6, respectively, totaling USD$16 for each set. The suggested installation density for this device on an exterior wall is 1 set/m^2; hence, the unit cost of application is USD$16/m^2. From the economic

perspective, this technology is currently expensive. To introduce this technology at minimum cost, critical areas, where the device must be first introduced should be identified through statistical analysis of common spots of deterioration on buildings' tiled exterior walls. Accordingly, costs can be reduced by installing this device at the more representative spots than installing them throughout the walls.

CONCLUSIONS

This study involved incorporating strain measurement technology to inspect the deterioration of tiled exterior walls. The results are as follows. (1) From the sound diagnostics experiment, the voiceprint-based eigenvalues of the tiled exterior walls with deterioration rates of 0%, 30%, and 70% were obtained. (2) Strain measurement results were analyzed and converted into a diagram of the deterioration symptoms of square tiles. This diagram was then analyzed using the pathogenesis theory of quasi pathogenesis. Cross-referencing various factors revealed that the eigenvalue of deterioration strain ranged from 0.015 to 0.05. Acute damage can be determined according to the rate attribute of square tile symptom development. (3) The strain measurement technique was confirmed to be applicable for measuring the deterioration of the tiled exterior walls. The unit cost of this technique is USD\$16/m^2. The cost can serve as a reference for the future application of this technique for smart exterior walls. The aforementioned results can serve as references for administrators in diagnosing the heath conditions of tiled exterior walls. In addition, this innovative technology is in line with the development of future smart buildings and can facilitate innovations in smart exterior walls. This study suggests that future studies can determine the effects of various environmental factors on the deterioration of tiled exterior walls by using the etiology determined through advanced quasi pathology. For example, the effects of natural deterioration factors such as acid rain, sunshine, weathering, and temperature and humidity, can be explored. Moreover, prevalent wall-decorating materials from recent years, such as various types of tiles and paint coating, can also be discussed to identify the pathogenesis of different materials and to plot relevant symptom diagrams.

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